OPTIMIZATION OF ABRASIVE MACHINING OF DUCTILE CAST IRON USING NANOPARTICLES: A MULTILAYER PERCEPTRON APPROACH

MUHAMMAD SAFWAN BIN AZMI

Report submitted in partial fulfillment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

JUNE 2012

ABSTRACT

This project was carried out to study the effects of using nanofluids as abrasive machining coolants. The objective of this project is to study the effect of nanocoolant on precision surface grinding, to investigate the performance of grinding of ductile iron based on response surface method and to develop optimization model for grinding parameters using artificial neural network technique. The abrasive machining process selected was surface grinding and it was carried out two different coolants which are conventional coolant and titanium dioxide nanocoolant. The selected inputs variables are table speed, depth of cut and type of grinding pattern which are single pass and multiple pass. The selected output parameters are temperature rise, surface roughness and material removal rate. The ANOVA test has been carried out to check the adequacy of the developed mathematical model. The second order mathematical model for MRR, surface roughness and temperature rise are developed based on response surface method. The artificial neural network model has been developed and analysis the performance parameters of grinding processes using two different types of coolant including the conventional as well as TiO_2nanocoolant. The obtained results shows that nanofluids as grinding coolants produces the better surface finish, good value of material removal rate and acts effectively on minimizing grinding temperature. The developed ANN model can be used as a basis of grinding processes.

ABSTRAK

Tujuan kajian ini dijalankan adalah untuk mengkaji kesan penggunaan cecair nano sebagai cecair penyejuk dalam proses abrasive machining. Objektif kajian ini adalah untuk mengkaji kesan penggunaan cecair nano dalam proses precision surface grinding, membuat kajian dalam prestasi grinding menggunakan ductile cast iron berpandukan response surface method dan untuk membina modal optimum bagi parameter yang telah dipilih menggunakan artificial neural network. Proses abrasive machining yang dipilih ialah precision surface grinding yang dilakukan menggunakan dua jenis cecair penyejuk yang berbeza iaitu cecair penyejuk konvensional dan cecair penyejuk nano titanium dioxide. Parameter input yang telah dipilih adalah kelajuan meja, kedalaman potongan dan corak grinding iaitu single pass dan multiple pass. Parameter yang dikaji pula adalah kenaikan suhu, kekasaran permukaan dan kadar pembuangan bahan. Analisa ANOVA juga dilakukan untuk membuat pengesahan ke atas model matematik yang dibina. Model matematik tahap dua yang dibina bagi setiap pembolehubah yang dikaji adalah dengan menggunakan RSM. Model ANN pula dibina untuk kedua-dua jenis cecair penyejuk yang berbeza bagi mengkaji kesan parameter yang berbeza. Daripada keputusan yang diperoleh, ia menunjukkan bahawa dengan menggunakan cecair penyejuk nano menghasilkan produk akhir yang baik dari segi surface finish, nilai yang memberangsangkan bagi MRR dan berkesan dalam meminimakan kenaikan suhu semasa proses grinding.

TABLE OF CONTENTS

	Page
SUPERVISOR'S DECLARATION	iii
STUDENTS DECLARATION	iv
ACKNOWLEDGMENTS	vi
ABSTRACT	vii
ABSTRAK	viii
TABLE OF CONTENTS	ix
LIST OF TABLES	xii
LIST OF FIGURES	xiii
LIST OF SYMBOLS	xv
LIST OF ABBREVIATIONS	xvi

CHAPTER 1 INTRODUCTION

1.1	Introduction	1
1.2	Problem Statement	3
1.3	Objectives	4
1.4	Scope of Project	4
1.5	Organization of Report	5

CHAPTER 2 LITERATURE REVIEW

2.1	Introduction	6
2.2	Grinding Wheels	6
2.3	Types of Grinding	8
2.4	Grinding Variables	11
2.5	Grinding Parameters	12
	2.5.1 Surface Roughness	12
	2.5.2 Grinding Temperature	12
	2.5.3 Material Removal Rate (MRR)	13
2.6	Nanofluids	14

2.6.1 Cooling Challenge 15

2.6.2 Nanofluids as Coolant 16

2.6.3 Titanium Dioxide 18

2.7 Preparation of Nanofluids 19

2.7.1 Two steps Process 19

2.7.2 One step Process 20

2.8 Artificial Neural Network Technique 20

CHAPTER 3 METHODOLOGY

3.1 Introduction 25

3.2 Workpiece Preparation 26

3.3 Workpiece Composition 28

3.4 Surface Grinding 29

3.5 Nanocoolant Preparation 30

3.6 Surface Roughness 30

3.7 Grinding Temperature 32

3.8 Design of Experiment (DOE) 32

3.9 Response Surface Method 33

3.10 Multilayer Perceptron Approach 36

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction 37

4.2 Response Surface Method 37

4.3 A Multilayer Perceptron Approach 40

4.3.1 Single Pass Grinding Pattern 40

4.3.2 Multiple Pass Grinding Pattern 43

4.4 Comparison between Conventional Coolant And 0.1% TiO_2 Nanocoolant 45

4.4.1 Single Pass Grinding Pattern 45

4.4.2 Multiple Pass Grinding Pattern 47

4.5 Microstructure Analysis 48

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion 51
5.2 Recommendations 52

REFERENCES 53

LIST OF TABLES

Table No.	Title	Page
2.1	Thermal conductivity of various materials	17
2.2	Comparison between microparticles and nanoparticles	18
3.1	Design of Experiment (DOE)	32
4.1	ANOVA results of Variance analysis for second order surface roughness in single pass and multiple pass using 0.1% titanium dioxide water based nanocoolant	39
4.2	Comparison between experimental value and predicted value for 0.1% TiO_2nanocoolant with multiple pass grinding pattern	40
4.3	Comparison between experimental value and predicted value (0.1% TiO_2)	40
4.4	Comparison between experimental value and predicted value (0.1% TiO_2) for single pass grinding pattern	42
4.5	Comparison between experimental value and predicted value (0.1% TiO_2) for multiple pass grinding pattern	45
4.6	Comparison of temperature, MRR, and surface roughness between conventional coolant and 0.1% TiO_2 nanocoolant for single pass grinding	46
4.7	Comparison of temperature, MRR, and surface roughness between conventional coolant and 0.1% TiO_2 nanocoolant for multiple pass grinding	47

LIST OF FIGURES

Figure No.	Title	Page
2.1	Schematic illustration of surface grinding process	7
2.2	Types of grinding	9
2.3	Contact resistance due to constriction of flow lines	12
2.4	Natural neurons (artist’s conception).	21
2.5	An artificial neuron	22
2.6	Architecture of an artificial neuron and a multilayered neural network	24
2.7	A Multilayer perceptron with two hidden layers	24
3.1	Initial form of workpiece	26
3.2	Desired form of workpiece	27
3.3	Milling Process	28
3.4	Precision surface grinder	29
3.5	Aluminum oxide grinding wheel	29
3.6	Preparation of nanocoolant	30
3.7	Measuring surface roughness using a perthometer	31
3.8	Scanning electron microscope	31
3.9	Tagged input parameters and output data	36
4.1	Surface roughness prediction plot	38
4.2	Desired output and actual network output for single pass grinding	41
4.3	Sensitivity analysis for single pass	41
4.4	Effect of network outputs for single pass grinding	42
4.5	Desired output and actual network output for multiple pass grinding pattern	43
4.6	Sensitivity about the mean for multiple pass grinding pattern	44

4.7	Network outputs for varied input table speed and depth of cut for multiple pass grinding pattern	44
4.8	0.1% TiO_2 nanocoolant(200x magnification)	48
4.9	Conventional Coolant (200x magnification)	49
4.10	0.1% TiO_2 nanocoolant (700x magnification)	50
4.11	Conventional Coolant (700x magnification)	50

LIST OF SYMBOLS

R_a	Surface Roughness

LIST OF ABBREVIATIONS

Al_2O_3	Aluminum Oxide
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
CBN	Cubic Boron Nitride
DOC	Depth of Cut
DOE	Design of Experiment
HTF	Heat Transfer Fluids
ID	Internal Diameter
MLP	Multilayer Perceptron
MRR	Material Removal Rate
RSM	Response Surface Methodology
SEM	Scanning Electron Microscopy
SiC	Silicon Carbide
TiO_2	Titanium Dioxide
TS	Table speed

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Grinding is a material removal and surface generation process used to shape and finish components made of metals and other materials. The precision and surface finish obtained through grinding can be up to ten times better than with either turning or milling. Grinding employs an abrasive product, usually a rotating wheel brought into controlled contact with a work surface. The grinding wheel is composed of abrasive grains held together in a binder. Heat generation is an important factor in the grinding process. It can degrade the integrity of the wheel matrix and/or abrasive, reduce workpiece surface quality by causing thermal cracks or burning of the surface, introduce strength reducing tensile residual stresses, and creates dimensional inaccuracies. Temperature may also influence the grinding mechanism either by softening the material or by introducing phase transformations. This is one of the important output parameters that will be observed where it will be influenced widely on the usage of nanocoolants. A large volume of grinding fluid is most commonly used to flood the grinding zone, hoping to achieve tangible productivity targets while often neglecting the seemingly fewer tangible environmental safety hazards. In addition, the inherent high cost of disposalor recycling of the grinding fluid becomes another major concern, especially as the environmental regulations get stricter. Minimizing the quantity of cutting fluid is desirable in grinding.

Cooling is one of the most important technical challenges facing many diverse industries. Technological developments such as microelectronic devices with smaller (sub-100 nm) features and faster (multi-gigahertz) operating speeds, higher-power engines and brighter optical devices are driving increased thermal loads, requiring advances in cooling. The conventional method for increasing heat dissipation is to increase the area available for exchanging heat with a heat transfer fluid. However, this approach requires an undesirable increase in the thermal management system's size. There is an urgent need for new and innovative coolants with improved performance. The novel concept of 'nanofluids' – heat transfer fluids containing suspensions of nanoparticles – has been proposed as a means of meeting these challenges (Keblinski et al., 2005). Heattransfer fluids have many industrial and civil applications, including in transport, energy supply, air-conditioning and electronic cooling, etc. Research and development activities are being carried out to improve the heat transport properties of fluids. Solid metallic materials, such as silver, copper and iron, and non-metallic materials, such as alumina, CuO, SiC and carbon nanotubes, have much higher thermal conductivity's than HTFs (Maxwell, 1873). At the very beginning, solid particles of micrometer, even millimeter magnitudes were blended into the base fluids to make suspensions or slurries. However, large solid particles cause troublesome problems, such as abrasion of the surface, clogging the microchannels, eroding the pipeline and increasing the pressure drop, which substantially limits the practical applications. Actually, liquid suspension was primarily a theoretical treatment only of some theoretical interest, and subsequent studies by other researchers achieved minor success. The large size of the particles and the difficulty in production of small particles were limiting factors (Han, 2008).

Nanofluids are solid-liquid composite materials consisting of solid nanoparticles with sizes typically of 1-100 nm suspended in liquid. Nanofluids have attracted great interest recently because of reports of greatly enhanced thermal properties. Conventional particle-liquid suspensions require high concentrations (>10%) of particles to achieve such enhancement (Das et al., 2008). Key features of nanofluids that have been reported to so far include thermal conductivities exceeding those of traditional solid/liquid suspensions; a nonlinear relationship between thermal conductivity and concentration in the case of nanofluids containing carbon nanotubes; strongly temperature-dependent thermal conductivity; and a significant increase in critical heat flux in boiling heat transfer. Each of these features is highly desirable for thermal systems; a stable and easily synthesized fluid with these attributes and acceptable viscosity would be a strong candidate for the next generation of liquid coolants (Das et al., 2008).

In recent years, there is increasing interest in using artificial neural networks (ANNs) for modelling and optimization of machining process (Madic et al., 2011). Analytical models are developed based on many simplified assumptions. It is sometimes difficult to adjust the parameters of the above mentioned models according to the actual situation of the machining process. Therefore, an artificial neural networks can map the input/output relationships and possess massive parallel computing capability, have attracted much attention in research on machining processes. ANN provides significant advantages in solving processing problems that require real-time encoding and interpretation of relationships among variables of high-dimensional space. ANN has been extensively applied in modeling many metal-cutting operations such as turning, milling and drilling. The general ability of the network is actually dependent on three factors. These factors are the selection of the appropriate input/output parameters of the system, the distribution of the dataset, and the format of the presentation of the dataset to the network. The selection of the neuron number, hidden layers, activation function and training algorithm are very important to obtain the best results (Razak et al., 2010).

1.2 PROBLEM STATEMENT

Nowadays, nanotechnology is becoming a fast paced development in the science and engineering world. Cooling is one of the most important technical challenges facing many diverse industries. Technological developments suchas microelectronic devices with smaller (sub-100 nm) features and faster (multi-gigahertz) operating speeds, higher-power engines, and brighter optical devices are driving increased thermal loads, requiring advances in cooling. The same goes to the grinding process where it also requires the use of coolant to provide quality work. The conventional method for increasing heat dissipation is to increase the area available for exchanging heat with a heat transfer fluid. However, this approach requires an undesirable increase in the thermal management system’s size. There is an urgent need for new and innovative coolants with improved performance. The grinding method used in this experiment is surface grinding. Surface grinding produces flat, angular, or contoured surfaces by feeding work in a horizontal plane beneath a rotating grinding wheel. Work is most often magnetically attached to the table, and may be ground by either a traversing or rotating movement of the table. Most surface grinding machines use a horizontal spindle which adjusts up and down allowing either the edge or the face of the wheel to contact the work. The novel concept of ‘nanofluids’ – heat transfer fluids containing suspensions of nanoparticles – has been proposed as a means of meeting these challenges. Nanofluids have the potential to be the next generation of coolants due to their higher thermal conductivities. The selection of appropriate base fluid is very critical in the application of nanoparticle based lubricants in grinding. A proper selection of the cutting parameters for machining to obtain performances similar to flood lubricated conditions is studied. The reason this title is chosen is because of the interest in the nanotechnology fields where it has been fast developing in the engineering field.

1.3 OBJECTIVES OF THE PROJECT

The objectives of the project are as follows:

(i) To study the effect of titanium dioxide (TiO_2) nanocoolant on precision surface grinding.

(ii) To investigate the performance of grinding of ductile iron based on response surface method.

(iii) To develop optimization model for grinding parameters using multilayer perceptron technique.

1.4 SCOPE OF PROJECT

The artificial neural network technique is used to prepare the design of experiments and find the optimum parameters. In the experiment, the material used is cast iron where it is grinded based on certain input parameters and the desired output parameters are observed. The input parameters of the experiment consist of four parameters includinggrinding pattern, table speed,depth of cut and type of coolant. The output parameters consist of three parameters including the surface roughness of the workpiece, temperature and material removal rate. For this experiment, the grinding process using conventional coolant is carried out. After the data is collected, the grinding process is carried out using TiO_2 nanocoolant. The both data collected, the surface roughness and material removal rate analysis is performed. Then, the data will be analyzed using response surface method and multilayer perceptron approach.

1.5 ORGANIZATION OF REPORT

Chapter 1 contains the introduction, problem statement, project objectives, scope of project and organization of report. Chapter 2 contains the literature review of the report based on studies of published papers and books that are related to the project. Chapter 3 is the methodology of the report which contains the methods used in completing the project. Chapter 4 contains the results and analysis obtained from the project. Chapter 5 is summarized the finding and recommended for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter is briefly explained about the basic grinding process, the input parameters including the grinding patterns, table speed, depth of cut and type of coolant, the output parameters, including the surface roughness, grinding temperature and material removal rate and also the difference between conventional coolants and nanocoolants. Grinding is a material removal and surface generation process used to shape and finish components made of metals and other materials. The precision and surface finish obtained through grinding can be up to ten times better than with either turning or milling. Grinding employs an abrasive product, usually a rotating wheel brought into controlled contact with a work surface. The grinding wheel is composed of abrasive grains held together in a binder. These abrasive grains act as cutting tools, removing tiny chips of material from the work. As these abrasive grains wear and become dull, the added resistance leads to fracture of the grains or weakening of their bond. The dull pieces break away, revealing sharp new grains that continue cutting.

2.2 GRINDING WHEELS

Figure 2.1 shows schematic illustration of surface grinding process (Shen et al., 2008). Grinding wheels are categorized by the type of abrasive they contain. The grinding process utilizes these abrasive particles as cutting edges in random contact with the material to be worked. The two major categories of grinding wheels are conventional and super-abrasive. The conventional grinding wheels are low performance and contain lower-cost abrasives such as aluminum oxide (Al_2O_3) and silicon carbide (SiC). The super-abrasive wheels are higher performance and contain high-cost abrasives consisting of diamond or cubic boron nitride (CBN). In many applications, manufacturing industries cannot achieve their productivity goals with conventional grinding wheels. The use of a super abrasive grinding wheel is prohibitively expensive and complex for many machine shops. Therefore, a limited number of manufacturing companies are using super-abrasive wheels in their grinding operations (Krueger et al., 2000).

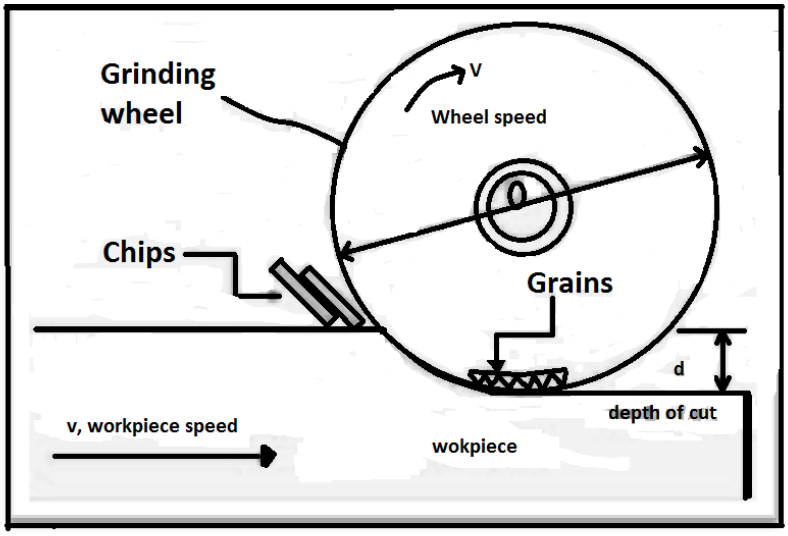


Figure 2.1: Schematic illustration of surface grinding process (Shen et al., 2008)

Most abrasives used in industry are synthetic. Aluminum oxide is used in three quarters of all grinding operations, and is primarily used to grind ferrousmetals. Next is silicon carbide, which is used for grinding softer, non-ferrousmetals and high density materials, such as cemented carbide or ceramics. Super abrasives, namely cubic boron nitride or "CBN" and diamond, are used inabout five percent of grinding. Hard ferrous materials are ground with "CBN" while non-ferrous materials and non-metals are best ground with diamond.The grain size of abrasive materials is important to the process. Large coarsegrains remove material faster, while smaller grains produce a finer finish.Wheels are graded according their strength and wear resistance. A "hard" wheelis one that resists the separation of its individual grains. One that is toohard will wear slowly and present dulled grains to the work and overheat,affecting the final finish. Another aspect of grinding wheels is their pore structure or density, which refers to the porosity between individual grains. This pore structure creates spaces between the grains that provide coolant retention and areas for the chips to form. Dense wheels are best for harder materials, while more open densities are better for the softer metals.The three factors of grain size, bond type, and pore structure are closely related, and together determine how well a wheel will perform. Damaged wheels or even wheels suspected of being damaged should not be used.

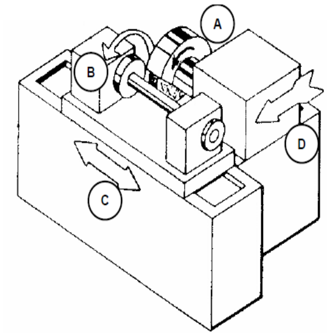
Wheel dressing and truing is done with special tools designed for that purpose. Although wheel dressing is often done manually between work cycles, some grinding machines perform the dressing task automatically.The application of coolants to the grinding process is important. Coolants reduce grinding machine power requirements, maintain work quality, stabilize part dimensions, and insure longer wheel life. Coolants are either emulsions, synthetic lubricants or special grinding oils. Coolants are applied by either flooding the work area or by high pressure jet streams.

2.3 TYPES OF GRINDING

There are many forms of grinding, but the four major industrial grinding processes are as follows:

- Cylindrical grinding
- Internal grinding
- Centerless grinding
- Surface grinding

These types of grinding are shown in Figure 2.2. In cylindrical grinding, the workpiece rotates about a fixed axis and the surfaces machined are concentric to that axis of rotation. Cylindrical grinding produces an external surface that may be either straight, tapered, or contoured. The basic components of a cylindrical grinder include a wheelhead, which incorporate the spindle and drive motor; a cross-slide, that moves the wheelhead to and from the workpiece; a headstock, which locates, holds, and drives the workpiece; and a tailstock, which holds the other end of the work.



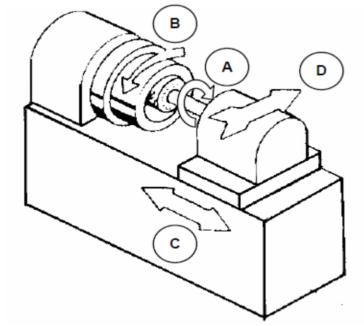
A: rotation of grinding wheel

B: work table rotation

C: reciprocation of worktable

D: Infeed

(a) Cylindrical grinding



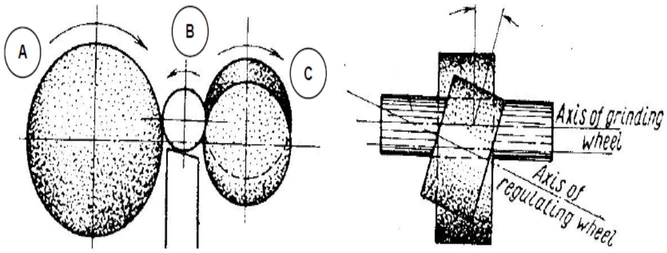
A: rotation of grinding wheel

B: workpiece rotation

C: reciprocation of worktable

D: infeed

(b) Internal Diameter Grinding

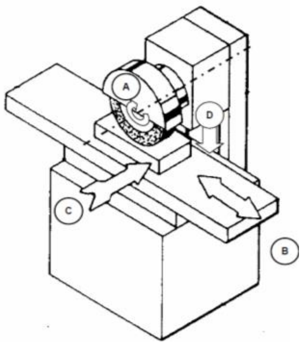


A: rotation of grinding wheel

B: workpiece rotation

C: reciprocation of worktable

(c) Centerless Grinding



A: rotation of grinding wheel

B: reciprocation of worktable

C: transverse feed

D: downfeed

(d) Surface grinding

Figure 2.2: Types of grinding

Internal diameter grinders (Figure 2.2(b)) finish the inside of a previously drilled, reamed, or bored hole, using small grinding wheels at high RPM. The principle elements of an internal grinding machine are the workhead, which holds the work and has its own drive, and the wheelhead, which is the internal grinding spindle. In addition to the rotary motions of work and wheel, an internal grinder has a traverse movement to bring the wheel to and from the work zone, and a reciprocating spindle movement for both the wheel's approach to the work surface and for the feed movement of the wheel during grinding. Several different internal contours can be produced within a workpiece using I.D.grinding.

In centerless grinding (Figure 2.2(c)), the workpiece rotates between a grinding wheel and aregulating drive wheel. The work is supported from below by a fixed work-rest blade. The two basic modes of centerless grinding are "thru-feed" and "in-feed". In the thru-feed mode, the work proceeds in the axialdirection through the slowly narrowing gap between the grinding wheel and the regulating wheel. Work is advanced by the axial force exerted on it by therotating surface of the regulating wheel. This is a highly productive form ofgrinding in that a number of workpieces can be ground simultaneously and in a continuous stream. The "infeed" mode is used for work with projecting heads that would prohibit "thru-feeding," the work is placed on the work-rest blade whileone wheel is retracted and fed to an end stop. The wheel is then brought back, reducing the gap between the wheels, grinding the work.

Surface grinding (Figure 2.2 (d)) produces flat, angular, or contoured surfaces by feeding workin a horizontal plane beneath a rotating grinding wheel. Work is most often magnetically attached to the table, and may be ground by either a traversing or rotating movement of the table. Most surface grinding machines use a horizontal spindle which adjusts up and down allowing either the edge or the face of the wheel to contact the work. Workpiece surfaces produced by grinding are influenced by the following factors:

- Workpiece material - harder materials allow finer finishes
- Type of wheel - fine grains yield finer finishes
- Dressing procedure - improperly dressed wheels will mar the work surface
- Feed rate - finer finishes are obtained with slower feed rates

- Machine rigidity - older, worn machines yield a poor quality finish
- Wheel condition - clogged wheels cannot produce a good finish
- Lubricant cleanliness - coolant filtration removes waste that could damage workpiece surface

2.4 GRINDING VARIABLES

The grinding process consists of several variables or parameters that affect the results of the experiment. The parameters were selected based on their availability through equipments and machinery capability available.

Grinding Pattern: There are two types of grinding pattern which are single pass and multiple pass. Single pass is defined when the grinding wheel passes along the grinding surface of the workpiece at a certain depth of cut only once. On the other hand, multiple pass is defined when the grinding wheel passes along the grinding surface of the workpiece ten times at a certain depth of cut.

Depth of Cut: Depth of cut is the determination of the depth of the grinding wheel into the workpiece at y-axis or vertically. It is done at depths of 20 µm, 40 µm and 60 µm.

Workpiecespeed: The workpiece speed is considered as a variable. There are three workpiece speed selected for this experiment which are 20, 30 and 40 m/s.

Types of Coolant: Most grinding machines are equipped with coolant systems. The coolant is directed over the point of contact between the grinding wheel and the work. This prevents distortion of the workpiece due to uneven temperatures caused by the cutting action. In addition, coolant keeps the chips washed away from the grinding wheel and point of contact, thus permitting free cutting. In this project, two types of coolants are used which are 5% soluble oil water-based conventional coolant and 0.1% titanium dioxide nanocoolant. The grinding results using these two different coolants will then be compared to see the effect of using nanocoolants instead of conventional coolants.

2.5 GRINDING PARAMETERS

From the manipulated parameters, the selected response parameters are surface roughness, grinding temperature and material removal rate (MRR) are discussed in the following section.

2.5.1 Surface Roughness

Characterization of surface topography is important in applications involving friction, lubrication, and wear (Thomas, 1999). In general, it has been found that friction increases with average roughness. The effect of roughness on lubrication has been studied to determine its impact on issues regarding lubrication of sliding surfaces, compliant surfaces, and roller bearing fatigue. Another area where surface roughness plays a critical role is contact resistance (Thomas, 1999). Thermal or electrical conduction between two surfaces in contact occurs only through certain regions. In the case of thermal conduction, the heat flow lines are squeezed together at the areas of contact, which results in a distortion of the isothermal lines, as illustrated in Figure 2.3.

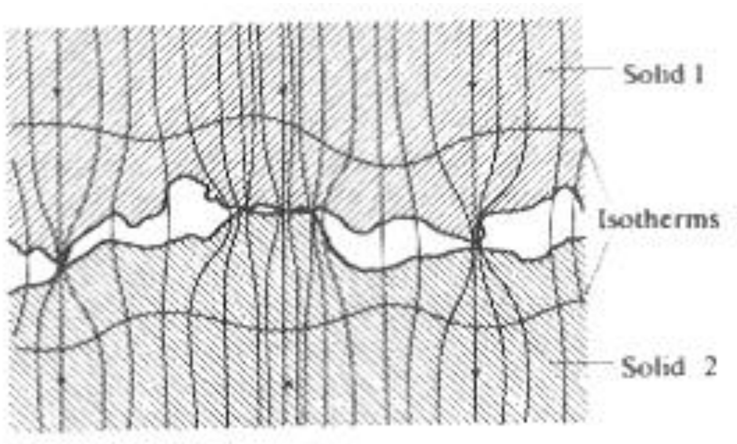


Figure 2.3: Contact resistance due to constriction of flow lines (Thomas, 1999)

2.5.2 Grinding Temperature

Heat generation is an important factor in the grinding process. It can degrade the integrity of the wheel matrix and/or abrasive, reduce workpiece surface quality by causing thermal cracks or burning of the surface, introduce strengthreducing tensile residual stresses, and creates dimensional inaccuracies. Temperature may also influence the grinding mechanism, either by softening the material or by introducing phase transformations. This is one of the important output parameters that will be observed in this project where it will be influenced widely on the usage of nanocoolants.

When a grinding grit engages the workpiece, it first causes deformation. This stage is known as plowing. The stress level becomes great enough, chip formation begins. Finally, the chip breaks loose and is carried out of the grinding zone by grinding fluid. The fluid serves both to remove chips, collectively known as swarf, and to cool the workpiece. Cooling is often critical in grinding because a significant amount of heat is typically generated in the process. Heat is generated primarily by three actions. First is shearing or fracture of the workpiece during chip formation. Second is the friction of the chip sliding at the grit's rake face. Lastly, heat is generated along the portion of the grit worn flat either by truing or by previous passes through the workpiece. Heat generated by any of these means, when it is localized near the grit or in the chip, is known as hot-spot (flash) temperature. Each grit acts as an asperity heat source, with conduction serving to distribute the heat from individual grits and raise the overall temperature of the grinding surface.

2.5.3 Material Removal Rate

Material removal rate is one the most important response parameter for abrasive machining. It is often desired to have maximum value of MRR. It is defined as the amount of mass removed from the workpiece over a period of time. In this experiment, MRR is calculated as Eq. (2.1)

$$MRR = \frac{\text{Initial mass - Final mass}}{\text{Grinding time}} \tag{2.1}$$